Responses to comments from Anonymus Referee #1

On „Use of dual-polarization weather radar quantitative precipitation estimation for climatology“ by Tanel Voormansik et al.(HESS-2019-624)

Referee’s comment

GENERAL COMMENTS

This study presents an evaluation of quantitative precipitation estimates based on dualpolarization radar measurements for 1h, 24h, and one-month durations. It is based on relatively long radar datasets collected from two radars located in two different places with different climate conditions. The results show the added value of dual-pol rainfall estimates compared with the traditional method based on the horizontal reflectivity only.

The focus on the paper is clearly on the evaluation of the performance of the method and as mentioned in the abstract the main application is hydrological forecast and early warning system. The use for climatology is not addressed and the datasets are actually not long enough to derive climatological information. I would recommend to change the title of the paper to reflect the actual scope of the study.

The paper is well organized and the study is relevant for the scientific community. However, there are some weaknesses and, in my view, the paper requires a major revision before publication. I recommend the following improvements:

- The description of the state of the art should be extended. Very little reference is made to previous studies on the evaluation of QPE based on dual-polarization measurements

- The description of the radar processing must be improved. Very little is said on the choice of various settings and parameters. Some tuning has been applied but without explained how it has been performed.

- The impact of some settings in the selection of the dataset and in the method for comparing and evaluating the various QPE methods should be tested.

- I would recommend to test the use of horizontal reflectivity without re-calibration based on dual-polarization data. This would allow to point out the benefit of such re-calibration.

- The impact of the 5-min to 15-min temporal sampling is addressed but the present study does not allow to isolate this effect from many other factors influencing the quality of the QPE. In the specific comments hereafter I propose a simple method that would allow to evaluate this impact. I recommend to test it.

- The main results of the study should be better presented in the abstract and the conclusion. What are the most original results of the study ?

Authors’ response

Authors would like to sincerely thank the referee for the time and effort spent in reading the initial manuscript and for making many clear and constructive suggestions for improvement. This helped a lot to improve the manuscript.

SPECIFIC COMMENTS

Abstract

Referee's comment

The length of the datasets should be mentioned in the abstract.

Authors' response

Agreed. Sentence about the length of the datasets added to the abstract.

Referee's comment

The use for climatology is not mentioned in the abstract and it is indeed not the main focus of the study.

The abstract should shortly present the main results of the study.

Authors' response

We agree with the comments. The short conclusion of main results was added to the abstract:

"Overall the radar products showed similar results in Estonia and Italy when compared to each other. The product where radar reflectivity and specific differential phase were combined based on a threshold exhibited the best agreement with gauge values on all accumulation periods. In both countries reflectivity based rainfall quantitative precipitation estimation underestimated and specific differential phase based product overestimated gauge measurements in general."

Referee's comment

1. Introduction

Satellite-based rainfall estimates are not only limited by the resolution but also by the accuracy of the estimates.

Authors' response

Agreed. Added short description with reference about the accuracy of the estimates to the manuscript:

"What is more, satellite-based precipitation estimates are limited by the accuracy of the estimates. The accuracy of the estimates has regional dependency and therefore can vary due to physiography of the study areas (e.g. precipitation climate, land use and geomorphology) (Petropoulos and Islam, 2017)."

Referee's comment

The dataset starts in 2011. This record is probably long enough to perform an evaluation of the quality but still too short to derive robust climatological information. Climatology is certainly one of the future applications of radar-based QPEs (e.g., Saltikoff et al., BAMS, 2019) and it should be mentioned here as one of the applications of QPEs next to nowcasting, hydrological forecasts or agriculture. Thera are very few references to similar studies evaluating the quality of dual-pol based QPE.

Authors' response

We agree that the dataset we had for the study is too short to derive robust rainfall climatology. Additional references to studies evaluating the quality of dual-pol based QPE were added:

"Previous studies where the benefits of dual polarimetric radar QPE have been shown are mostly based on selected short time periods or only single events (Wang and Chandrasekar, 2010; Chang et al., 2016; Cao et al., 2018)"

Referee's comment

2. Data and methods

2.1 Rain gauge measurements

Can you shortly describe how the measurements are quality-controlled?

Authors' response

Short description of the quality control process added to the manuscript.

Referee's comment

L74 : why and how is this subset selected ?

Authors' response

The rain gauge subset consists of gauges that are located within the range limit that is applied to the radar data which is explained in Section 2.3 where comparison framework is described.

Referee's comment

2.2 Weather radar precipitation estimates

One of the benefits of dual-pol measurements is the reduction of ground clutter. Is there any clutter filtering based on these measurements in the processing ?

Authors' response

Agreed. Short description of polarimetric filtering used on data added to the manuscript.

Referee's comment

L85 : why are KDP measurements unreliable at short range ?

Authors' response

To get reliable KDP estimations averaging among range bins is required. However, close to the antenna, stable and reliable observations are not available, due to both the antenna itself and TR-limiters response time (or the dual polar switch in case of alternate transmission). The explanation was added to the manuscript as well.

Referee's comment

L100: what happens after 2016 ?

Authors' response

Reworded the sentence so it would be unambiguously understood: “Bric della Croce observations used in the study range from 2012 to 2016 whereas observations from 2012 to 2013 are with ten-minutes interval and from 2013 to 2016 with five minutes interval time resolution.”

Referee’s comment

The processing of the raw PHIDP data to derive K_{DP} is only very briefly described. Some parameters have been tuned but we don’t know which and how. What is the impact of this tuning on the final results? Is there any impact of the PHIDP processing on the resolution in range? Is the final resolution appropriate for estimating heavy rainfall from convective cells with relatively small spatial extent? More must be said on how the optimal settings have been determined. Is the dataset used for verification independent of the dataset used for tuning?

Authors’ response

Following the referee comment several sentences to describe the derivation of KDP were added to the manuscript:

“With default parameter values the rays where differential propagation phase folding occurred did not unfold correctly and thus the function did not produce correct specific differential phase values. In order to fix the folding issue function parameters self_const (self-consistency factor) and low_z (low limit for reflectivity – reflectivity below this value is set to this limit) had to be tuned. The default values were 60000.0 and 10.0 respectively and after testing with various combinations of various values the values 12000.0 and 0.0 were found to produce optimal results and therefore were chosen for final calculations.”

Referee’s comment

The re-calibration of the horizontal reflectivity using the self-consistency theory should be a bit more explained even if a detailed description is available elsewhere. For example, is there also some fine tuning in this re-calibration ? The re-calibration is another benefit of dual-pol measurements and it would be interesting to show what is the impact on the quality of the derived QPEs. Comparisons of QPE derived from horizontal reflectivity with and without re-calibration would be very interesting. I recommend to include these comparisons.

Authors’ response

We agree that the paper would benefit from providing more details about the re-calibration method. As the comparisons of QPE with and without re-calibrated horizontal reflectivity would be out of the scope and focus of this paper we would not include it. Following the referee comment short explanation of the theory along with the used filtering thresholds was added to the manuscript:

“The method essentially compares the observed differential propagation phase ($\Phi_{DP}{}^{obs}$) to a calculated theoretical differential propagation phase ($\Phi_{DP}{}^{th}$). The data used for calibration had to be filtered using a number of restrictions: only data from June to September was allowed; data from 0.5° elevation and 10-70 km range only used; only bins where horizontal and vertical polarization channel correlation coefficient was over 0.92 were used; any bins where Φ_{DP} was greater than 12° were removed; whole ray where reflectivity was greater than 50 dBZ was removed; whole ray where Z_{DR} was greater than 3.5 dB was rejected; only rays where $\Delta \Phi_{DP}{}^{obs}$ was greater than 8° and where the consecutive rain path was at least 10 km was used; any scans in which precipitation occurred on top of the radome were removed.”

Referee's comment

L 127 : how is the 25 dBZ threshold selected?

Authors' response

The threshold was selected after testing on a few months dataset with various reflectivity levels and this provided the best correlation with gauges. Following the referee comment a short description was also added to the manuscript.

Referee's comment

2.3 Comparison framework

L 137 : 30 km seems very small. Why such a limited study area?

Authors' response

The applied range limit is aimed mainly at eliminating uncertainties due to complex orography, like shielding by the mountains. Up to 30 km from Bric della Croce terrain is relatively flat while beyond that mountains block most of the radar signal for lowest elevations. It is explained in manuscript Section 2.3.

Referee's comment

L 139 : hail is not considered as as possible precipitation type. Is this valid for Estonia? In the description of the comparison framework, nothing is said about the minimum rainfall amounts used for the selection of the valid pairs and the production of the statistics. A threshold of 0.1 mm is mentioned in the legend of the figures. Is this threshold used all through the study? It seems very small which means that some statistics might be strongly influenced by very small rainfall amounts. How do you apply this threshold? Should gauge and QPE values both exceed 0.1 mm to make the pair valid?

Authors' response

We agree that hail as solid precipitation type was overlooked. It is now added to the manuscript. A threshold of 0.1 mm is set and applied such that both gauge and radar QPE values must exceed this value to make the pair valid. It is used all through the study. This clarification is added to the manuscript.

Referee's comment

3. Results and discussion

3.1 Case comparisons

L157- 159 : unclear formulation

Authors' response

The formulation was changed so it would be more clearly understood.

Referee's comment

Figure 2 : the agreement between gauge and R(Z_H,K_{DP}) is almost perfect for this particular month. Does it give a realistic view on the results obtained in Estonia? Perhaps showing a few additional cases (perhaps, as a supplement) would allow to get a better picture of the overall agreement between gauge and QPE values?

Authors' response

We agree that Figure 2 might leave unrealistic view of the results obtained in Estonia. Another case was added to the manuscript Section 3.1 where the agreement between radar QPE and gauge was not so perfect.

Referee's comment

L188 – 196 : Can you further elaborate on random versus systematic errors . As statement like "Systematic errors cannot be excluded" seems somewhat obvious when it concerns radar-based rainfall estimates. In the paper, the word "randomness" seems to be used for expressing "scatter".

Authors' response

Systematic errors can originate for example from radar hardware calibration or unsuitable Z-R relationship (the actual drop size distribution is different than assumed in the Z-R relationship). Random errors can originate for example from incomplete beam filling, high intensity small scale rainfall events not completely resolved by the radar (spatial and/or temporal) resolution. Following the referee comment the word "scatter" was used in the paper instead of "randomness".

Referee's comment

L220. Many factors influence the scatter. The temporal sampling is one of them and the results shown here do not allow to isolate this effect. A proper way to test the impact of the temporal sampling on the scatter is possible with the Italian radar which produces a 5-min sampling dataset. A degraded dataset with 15-min temporal sampling can be produced by removing 2 out of 3 date files. The results obtained using the original 5-min and the degraded 15-min dataset would allow evaluating the impact of the temporal sampling.

Authors' response

We agree with the explanation and description of the methodology provided by the referee but decided to not include it in the study because it would be out of the scope and main focus of this study. Long accumulation datasets comprised of many years even out the errors, even on shorter accumulation periods but especially on longer periods.

Referee's comment

Figure 7 : two regimes seem to appear. Can you comment on this ?

Authors' response

The reviewer is right. The Bric della Croce weather radar is located on a top of hill at 770 m asl and during the winter season a vertical profile reflectivity correction (VPR) is applied (Koistinen, 1991). This correction is manually switched on at the beginning of the cold season and it is switched off at the end. In case of convective precipitation, this correction may lead to rainfall overestimation. On the other hand, stratiform cold precipitation is heavily underestimated when VPR correction is switched off. So, the VPR correction leads to these regimes. The separation between the two regimes could be obtained by reducing the study area even more, limiting the study to June, July and August. Unfortunately only the corrected reflectivity (including VPR) is available for studied years; later both corrected and uncorrected become available. The explanation was added to the manuscript as well.

Referee's comment

Figure 8 :why is a contour plot used here and not in the other figures ?

Authors' response

The same plotting function was used for all scatterplots (Python seaborn data visualization library function *kdeplot* with scatter), but only on Figure 8 the number of data points was low and distribution coarse enough to make contours clearly visible. We agree that the plots do not look uniform enough and we are going to remake them.

Referee's comment

Conclusion

L 306 : A fourth radar rainfall estimate would be useful : R(Z_H) without re-calibration based on dual-pol data.

Authors' response

While we agree that it would allow direct comparison of the reflectivity based rainfall estimates we would still not include it in this study because it would not add enough value to the comparison of other radar QPE products. Also the comparison results and conclusions would depend very much on radar calibration quality and it was not the focus of this paper to evaluate this.

Referee's comment

L 327-329 : the formulation is not very clear. What do you mean with "filtering the radar accumulations" ? It seems also that the conclusion is known before performing the study.

Authors' response

Agreed. Reworded the sentences.

Referee's comment

The conclusion does not make clear what are the original results of the present study.

Authors' response

Agreed. The conclusion was improved to make main original results of the study stand out more clearly.

Referee's comment

TYPOS AND FORMULATIONS

Discussion paper

Strange formulations and spelling errors are present throughout the text. Some are listed below. I would recommend having the text proofread by a native English speaker.

L 12 and further : precipitation without s all through the text

Authors' response

Agreed and corrected in manuscript.

Referee's comment

L16 : legacy ?

Authors' response

Agreed. Replaced the word "legacy" with a more suitable "'conventional".

Referee's comment

L 30 : to a good effect ?

Authors' response

The phrase was replaced with a word "successfully".

Referee's comment

L97 : central respect Piemonte : strange formulation

Authors' response

Agreed. Reworded the sentence to be more clear.

Cited references:

Cao, Q., Knight, M. and Qi, Y.: Dual-pol radar measurements of Hurricane Irma and comparison of radar QPE to rain gauge data, In Proceed. of the 2018 IEEE Radar Conference, Oklahoma City, OK, USA, 23-27 April 2018, 0496-0501, https://doi.org/10.1109/RADAR.2018.8378609, 2018

Chang, W.Y., Vivekanandan, J., Ikeda, K. and Lin, P.L.: Quantitative precipitation estimation of the epic 2013 Colorado flood event: Polarization radar-based variational scheme, J. Appl. Meteorol. Climatol., 55, 1477-1495, https://doi.org/10.1175/JAMC-D-15-0222.1, 2016

Koistinen, J.: Operational correction of radar rainfall errors due to the vertical reflectivity profile, in: Proceedings of the 25th Radar Meteorology Conference, American Meteorological Society, Paris, France, 91–96, 1991.

Petropoulos, G.P. and Islam, T.: Remote Sensing of Hydrometeorological Hazards. CRC Press, Boca Raton FL, USA, 2017.

Wang, Y. and Chandrasekar, V.: Quantitative precipitation estimation in the CASA X-band dual-polarization radar network, J. Atmos. Ocean. Technol., 27, 1665-1676, https://doi.org/10.1175/2010JTECHA1419.1, 2010.

Responses to comments from Referee #2

On „Use of dual-polarization weather radar quantitative precipitation estimation for climatology“ by Tanel Voormansik et al.(HESS-2019-624)

Referee’s comment

GENERAL COMMENTS

In this paper long-term datasets from two different regions (Estonia and Northern Italy) are used to evaluate the performance of polarimetric weather radar quantitative precipitation estimates. Several years of radar and gauge data are used for this. This is a very interesting topic that is highly relevant and timely as long-term high-quality operational polarimetric datasets are becoming more and more available. The paper has a clear focus, which makes it pleasant to read. Some of the English used in the paper could be improved, but it certainly does not prohibit full understanding of the paper. I do have some questions that I would like to see clarified and some suggestions for improvements. In particular, I think there may be an error in at least one of the figures that I think the authors should look at. I think the paper should be published after major revisions. Specific comments are given below.

Authors’ response

Authors would like to sincerely thank the referee for the time and effort spent in reading the initial manuscript and for making many clear and constructive suggestions for improvement. This helped a lot to improve the manuscript.

Referee’s comment

Specific comments

1. I very much appreciate the honesty of the authors about removing low-quality data from the dataset that resulted from radar issues. Because of this, and because of the focus on only the warm season, I doubt whether mentioning “climatology” in the title would be suitable. Please reconsider this, or at least add to the title that this is about warm-season precipitation (which is still very valuable).

Authors’ response

We agree with the comment. We decided to change the title to be more appropriate considering the length of the dataset used. The new proposed title is “Applicability of dual-polarization weather radar quantitative rainfall estimation for climatological purposes”.

Referee’s comment

2. On line 72, it is stated that the Italian rain gauges have a resolution of 0.2 mm and 1 minute. This means that, if the gauges report rainfall intensities, the minimum rainfall intensity that these gauges would be able to record is 12 mm h^{-1} . Or do the gauges record total rainfall accumulation with a 1-minute time resolution (in which case there is no issue with the total accumulations)?

Authors’ response

This is the recording resolution, measurement resolution is higher. Following the referee comment to make it more clear the sentence was rearranged as follows:

„The temporal resolution of the gauges network is 1-minute. The Arpa Piemonte weather stations are equipped with CAE PMB2 tipping-bucket rain gauges. Their resolution (0.2 mm) is the amount of precipitation for one tip of the bucket. The working range of measures is from zero mm to 300 mm/h with underestimation for high precipitation intensities. Such errors are corrected according to results of WMO Field Intercomparison of Rainfall Intensity Gauges (Vuerich et al., 2009)."

Referee's comment

3. On lines 105-107, the computation of Φ_{DP} and K_{DP} from raw Φ_{DP} is mentioned, along with the fact that "carefully tuned parameter values according to data specifics" are used for this. It would be interesting and highly relevant to include a more thorough description of this in the paper, especially since K_{DP} is a key variable in this paper. I think a one- or two-sentence summary of the method would be nice, along with a short description of the parameters and how they were determined.

Authors' response

Added a few sentences to describe the derivation of K_{DP}: "With default parameter values the rays where differential propagation phase folding occurred did not unfold correctly and thus the function did not produce correct specific differential phase values. In order to fix the folding issue function parameters *self_const* (self-consistency factor) and *low_z* (low limit for reflectivity – reflectivity below this value is set to this limit) had to be tuned. The default values were 60000.0 and 10.0 respectively and after testing with various combinations of various values the values 12000.0 and 0.0 were found to produce optimal results and therefore were chosen for final calculations."

Referee's comment

4. On lines 107-110, the self-consistency method for re-calibrating Z_H is discussed, where Z_{DR} is also used. Later, on lines 124-125, it is mentioned that the use of Z_{DR} for quantitative precipitation estimation is not recommended for C-band radars. I think it should be discussed here why Z_{DR} can be used for re-calibration of Z_H.

Authors' response

Agreed. Following the referee comment the following sentence was added to Section 2.2:

„Z_{DR} is not suitable for QPE on C-band radars, but it can be used in this calibration methodology after applying strict restrictions on the data used for this purpose."

Referee's comment

5. On line 127, the threshold for switching between $R(Z_H)$ and $R(K_{DP})$ is defined to be 25 dBZ for Z_H. Using Eqs (1) and (2), this threshold translates to $R \approx 1$ mm h−1 and $K_{DP} \approx 0.015°$ km−1. These values are much lower than what is cited from the literature ($R = 50$ mm h−1 and $K_{DP} = 0.5 - 1°$ km−1). What is the reason for using this much lower threshold? I think this should be explained in the paper.

Authors' response

We agree that an explanation would be suitable in the paper. Various thresholds were tested on our data and this performed the best. Following the referee comment the following sentence was added to the manuscript:

„The Z_H threshold value was selected after testing with various reflectivity levels. The threshold level is considerably lower than some of the thresholds used in the literature but on our datasets it performed the best."

Referee's comment

6. In Section 2.2, there is no mention of attenuation that could affect the R(Z_H) estimates. This attenuation could be corrected for using Φ_{DP}. Is there a specific reason why attenuation correction is not carried out?

Authors' response

We agree that it should be mentioned in Section 2.2 and explained why it is not used. Following the referee comment the following was added to the manuscript:

"The QPE of $R(Z_H)$ can be affected by attenuation on C-band radars especially in heavy precipitation and at long distances. While this can be corrected using Φ_{DP} in our study it was not applied to the reflectivity data in order to not introduce another possible source of error between the results of Estonia and Italy that could not be easily quantified. Effectiveness of attenuation correction using Φ_{DP} is hampered by its temperature, shape and size distribution dependence which affect the accompanying error (Vulpiani et al., 2008)."

Referee's comment

7. In Section 2.2, it would be good to mention that the effect of VPR will be limited in the analyses because only data from the warm season will be used, and that only data close to the radars (70 km and 30 km for Estonia and Italy, respectively) will be used.

Authors' response

Agreed. Following the referee comment the following sentence was added to Section 2.2:

"The QPE of R(Z_H) can also be affected by the effect of non-uniform vertical profile of reflectivity (VPR). In the current study the effect of VPR will be limited because only data from warm season was used and distance limits to the radar data were set (70 km for Estonia and 30 km for Italy, respectively)."

Referee's comment

8. In Section 2.2, it is not explicitly mentioned how precipitation accumulations are computed. I assume (also based on the rest of the paper) that they are computed by simply adding subsequent instantaneous radar QPE values, without any space-time interpolation. It would be good to mention that here explicitly.

Authors' response

Agreed. The clarification seemed to suit better to Section 2.3 where it was added to the earlier description of accumulation:

„Radar-based QPEs have been accumulated to 1-hour duration and longer durations have been calculated based on these accumulations. Accumulations were calculated by adding subsequent instantaneous radar QPE values without any space-time interpolation."

Referee's comment

9. Is my interpretation of Fig. 1 correct if I say that in Estonia only a circular area around the radar is used (up to 70 km range), while in Italy a rectangular area (60 × 60 km2) around the radar is used? If this is correct, is there an explanation of why two different areas have been used? This should be included in the paper.

Authors' response

We agree with the referee and thus the following explanation was added to the manuscript:

"As can be seen from Fig. 1 circular area around the radar is used in Estonia but in Italy rectangular area is used. The reason for this is that Orography in Piemonte is very complex ranging from flat plains in the Po valley (about 100 m a.s.l.) to the Alps up to more than 4,000 m a.s.l. The Bric della Croce weather radar is located on Torino hill that is about 30 km from the Alps. Therefore, the elegant and simple limitation in range by some kilometers from the radar site does not work. To avoid mountainous areas, where partial and total beam-blocking, heavy ground contamination increases, a rectangle area, that extends towards flat grounds, has been preferred."

Referee's comment

10. Equation (3) for Pearson's correlation coefficient is incorrect. It should be: CC = Xn i=1 (ri − rm) (gi − gm) vuutXn i=1 (ri − rm) 2 vuutXn i=1 (gi − gm) 2 .

Authors' response

We would like to thank the referee for pointing that out. The Equation (3) was corrected accordingly in the manuscript.

Referee's comment

11. For the definition of the normalized mean error in Eq. (4), the multiplication with 100% needs to be omitted in order to make it consistent with the results presented in Tables 1-6. I would also like to suggest renaming this statistic to the "normalized mean absolute error", which in my view is closer to what it actually is.

Authors' response

We would like to thank the referee for pointing the error out and we agree with the suggestion of renaming the statistic. Manuscript was edited according to the suggestions.

Referee's comment

12. The authors could consider to also normalize the RMSE in Eq. (6) with the mean gauge rainfall. In this way, all statistics will be dimensionless. This is of course just a choice, and I would also be perfectly fine with leaving the definition as it is.

Authors' response

We thank the referee for the suggestion but decided to leave the definition as it is.

Referee's comment

13. On lines 192-193, the cause for the more severe underestimation of R from Z_H in Italy than in Estonia is said to be the fact that there is more intense precipitation. However, doesn't this mean that the employed Z − R relation is not suitable? Differences in raindrop size distribution (DSD)

climatologies between Estonia and Italy may also cause differences. So it would be good to comment here on the suitability of the retrieval relations (Eqs (1) and (2)) for both regions.

Authors' response

We agree that the retrieval relations are definitely a cause for differences among the two regions. The rationale behind using the same relations for both regions was the fact that rainfall retrieval relations always entail errors with them anyway and we wanted to keep the comparison as straightforward and homogeneous as possible. Following the referee comment the following sentences were added to Section 3.1:

„Another cause of differences between the two countries might be differences in the drop size distribution climatologies. Rainfall retrieval relations also entail errors and to keep the comparison as uniform as possible we decided to use the same relations for both Italy and Estonia."

Referee's comment

14. On lines 198-199, it is stated that using different time intervals can help in understanding the effect of temporal sampling differences between radar and gauges. While this is certainly true, it should also be noted that using longer accumulation intervals will also lead to less severe errors (compensating underestimates and overestimates; the R(K_{DP}) curve in Fig. 3 is a good example of this). I think a remark about this should also be added to the text. The same holds for line 219.

Authors' response

Agreed. Following the referee comment the following sentence was added to Section 3.3:

„Using longer accumulation intervals leads to less severe errors as the longer period compensates for both underestimates and overestimates."

Referee's comment

15. On lines 215-217, an important statement is made about the improvement that R(Z_H, K_{DP}) gives over the other methods. At first reading, I thought that this statement is too bold given the results presented in Table 1, but on second thought it is correct. What would have helped me is if something along the lines of "(i.e., each statistic is approximately as good at the best of the other two)" after "...other product's weak points" would have been included. You could consider including this here.

Authors' response

We agree that the explanation should be improved. Reworded the sentence as follows:

"R(Z_H,K_{DP}) shows considerable improvement by combining strong aspects of the two methods"

Referee's comment

16. In Fig. 5, it is interesting to see that of the 4 highest 1-hour accumulations measured by a gauge, 3 of them have significantly higher radar estimates for R(Z_H, K_{DP}) than either R(Z_H) or R(K_{DP}). This means that for R(Z_H, K_{DP}), probably the best estimator of R is selected for most of the intervals (i.e., for at least one of the underlying 5-minute intervals R(Z_H) is higher than R(K_{DP}), and it is correctly selected for R(Z_H, K_{DP})). I think this merits some more discussion in the paper, especially since this is the case for 3 of the 4 highest 1-hour accumulations.

Authors' response

We agree that pointing this out together with additional explanation would be useful. Following text was added to the manuscript:

"Although from Fig. 5 it can be noticed that of the four highest 1-hour accumulations measured by the gauge, three of them have significantly higher radar estimates for $R(Z_H,K_{DP})$ than either $R(Z_H)$ or $R(K_{DP})$. This could be explained by precipitation that was very variable in intensity and also in spatial coverage in these three cases which in turn caused unsteady behaviour of the precipitation estimates. Z_H underestimates high intensities, but with low intensities K_{DP} becomes noisy and the rainfall intensity estimation is not feasible. Finally, to reduce K_{DP} uncertainties range averaging is mandatory, leading to underestimation in case of very localized showers. By blending both $R(Z_H)$ and $R(K_{DP})$, a better rainfall estimation is expected."

Referee's comment

17. On lines 242-243, it is stated that the normalized bias is much smaller for the 24- hour accumulations than for the 1-hour accumulations. However, looking at the definition of the NMB in Eq. (5), there should be absolutely no difference between the two, if the same underlying samples have been used (i.e., it makes no difference whether you first sum over 24 hours, and then subtract gauge from radar sums, or if you compute the difference first and then sum over 24 hours because subtraction is a linear operation). So what is the cause of these differences? Is it because you use different underlying samples, possibly by taking only accumulations above 0.1 mm (see captions of Figs 4 to 7)? If this is the case, this stresses the importance of low-intensity rain for total rainfall accumulations. This should be explained clearly. The same holds for differences between 24-hour and 1-month accumulations.

Authors' response

The cause is most probably different underlying samples. The 0.1 mm threshold is applied after the accumulation as a last step before calculating the verification metrics. This means that the total accumulated precipitation sum is larger in 24h accumulation dataset than in 1h dataset (although the difference is not big, 10900 mm vs 10200 mm in case of Estonia and gauge measurements). Following the referee comment the following was added to the manuscript:

"By looking at the definition of NMB in Eq. (5) it can be seen that in case the same underlying samples are used NMB should be equal on all accumulation lengths. In our study the underlying samples were different as the 0.1 mm threshold was applied after the accumulation as a last step before calculating the verification metrics. This emphasizes the importance of low-intensity precipitation for total accumulations."

Referee's comment

18. If I compare the NMB presented for $R(Z_H)$ in Table 3 and the corresponding panel in Fig. 6, I'm surprized at the fact that the underestimation by the radar is so small. Is this because there is an extremely high density of points just above the black line close to 0 mm in Fig. 6?

Authors' response

Rechecking the dataset and recalculating the NMB gave the same results so the reason behind it must be high density of points above and near the black line on low accumulation values.

Referee's comment

19. Comparison of Figs 5 and 7 gives me the feeling that there may be an error in one of them. For example, if I roughly add all of the accumulations from $R(Z_H)$ in Fig. 5, the resulting amount of rain is

much smaller than when I roughly add all of the accumulations from $R(Z_H)$ in Fig. 7. Furthermore, the number of accumulations exceeding 0.1 mm given in the caption is higher for Fig. 7 than for Fig. 5. This is impossible unless a different dataset has been used. So I suggest to take another careful look at the figures and the results presented in the tables.

Authors' response

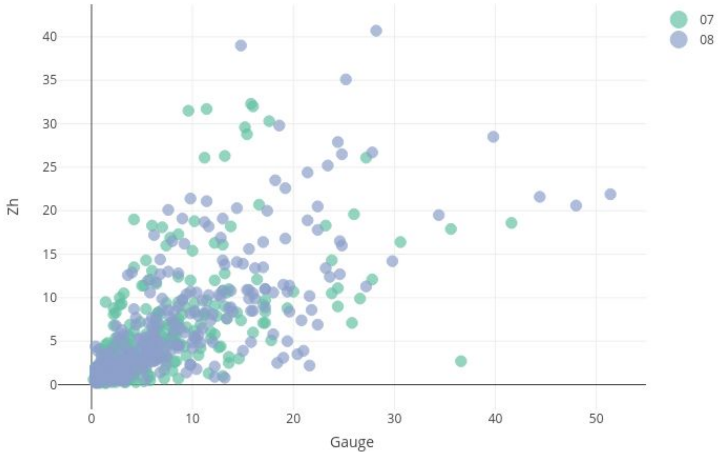
The comparison between radar and raingauge is carried out only if both the gauge measurement and the radar estimation are simultaneously greater than 0.1 mm; otherwise, this comparison loses meaning. Here, short duration and scattered precipitations are considered (i.e. few rain gauges record rainfall during an event). When the rainfall accumulation interval decreases, the number of valid couples (i.e. both greater than zero) tends to decrease. That's the reason because the number of samples is greater in Figure 7 than in Figure 5. As all invalid couples are discharged, it has no meaning to compare the total accumulation between these plots.

Referee's comment

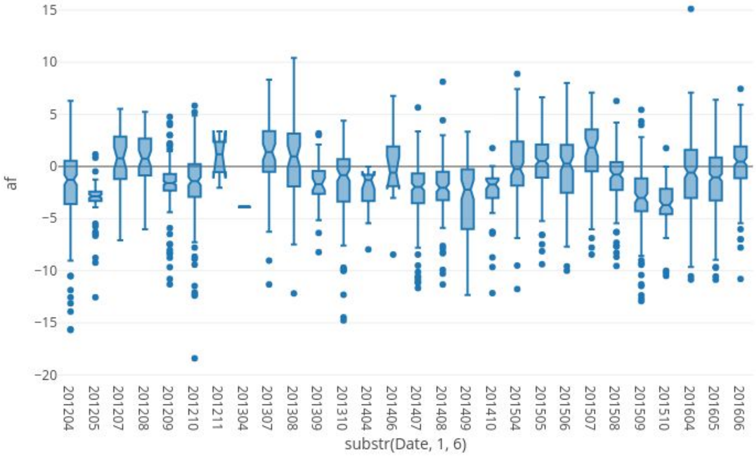
20. Figure 7 seems to show two regimes for $R(Z_H)$, where one overestimates and the other underestimates for higher rainfall accumulations. It would be interesting to discuss this in the paper. I'm interested to learn if these regimes are separable by some other variable such as time, temperature, or something else.

Authors' response

The reviewer is right. The Bric della Croce weather radar is located on a top of hill at 770 m asl and during the winter season a vertical profile reflectivity correction (VPR) is applied (Koistinen, 1991). This correction is manually switched on at the beginning of the cold season and it is switched off at the end. In case of convective precipitation, this correction may lead to rainfall overestimation. On the other hand, stratiform cold precipitation is heavily underestimated when VPR correction is switched off. So, the VPR correction leads to these regimes in daily comparison (Figure 7). The separation between the two regimes could be obtained by reducing the study area even more and limiting the study to June, July and August. Unfortunately, the corrected reflectivity (including VPR) is available for studied years only; later both corrected and uncorrected become available. The following Figure shows the same scatterplot as in the paper but limited to summer months July and August 2012-2016.



The double regime induced by VPR correction disappears. However, if we consider the logarithmic ratio between rainfall estimated by weather radar and measured by gauge ($af = 10\ log10(R/G)$), it is clearly visible a seasonality with underestimation (on average) for April, May and October and November and slight overestimation during warm months.



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~~Use of dual-polarization weather radar quantitative precipitation estimation for climatology~~Applicability of dual-polarization weather radar quantitative rainfall estimation for climatological purposes

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Abstract. Accurate, timely and reliable precipitation observations are mandatory for hydrological forecast and early warning systems. In the case of convective precipitation~~s~~, traditional rain gauges networks often miss precipitation maxima, due to density limitations and high spatial variability of rainfall field. Despite several limitations like attenuation or partial beam-blockings, the use of C-band weather radar has become operational in most of European weather services. Traditionally, weather radar-based quantitative precipitation estimation (QPE) are derived by horizontal reflectivity data. Nevertheless, dual-polarization weather radar can overcome a number of shortcomings of the conventional~~legacy~~ horizontal reflectivity based estimation. As weather radar archives are growing they are becoming increasingly important for climatological purposes in addition to operational use. For the first time, the present study analyses one of the longest datasets from fully operational polarimetric C-band weather radars; those ones are located in Estonia and in Italy, in very different climate conditions and environments. The length of the datasets used in the study is 5 years for both Estonia and Italy. The study focuses on long-term observations of summertime precipitation and their quantitative estimations by polarimetric observations. From such derived QPEs accumulations for 1 hour, 24 hours and one month durations are calculated and compared with reference rain gauges to quantify uncertainties and evaluate performances. Overall the radar products showed similar results in Estonia and Italy when compared to each other. The product where radar reflectivity and specific differential phase were combined based on a threshold exhibited the best agreement with gauge values on all accumulation periods. In both countries reflectivity based rainfall quantitative precipitation estimation underestimated and specific differential phase based product overestimated gauge measurements.

1. Introduction

Detailed surface rainfall information is of great importance in many fields not only for agricultural or hydrological applications but also for assimilation purposes within numerical weather models and climatologies. For decades gauge networks have provided the best reference datasets. E-OBS 50-years daily European gridded interpolated dataset has been widely used in climatological studies (Cornes et al., 2018). Gauge based datasets have well known shortcomings in their low spatial and to a lesser degree temporal resolution. Precipitation data from satellites provides good spatial coverage, but still not in very high temporal resolution, especially in higher latitudes (Sun et al., 2018). Polar orbiting satellites provide better spatial resolution data in higher latitudes, but they are very limited in temporal resolution (Tapiador et al., 2018). What is more, satellite-based precipitation estimates are limited by the accuracy of the estimates. The accuracy of the estimates has regional dependency and therefore can vary due to physiography of the study areas (e.g. precipitation climate, land use and geomorphology) (Petropoulos and Islam, 2017). Now that weather radars have been used already for decades in many countries their archives are getting long enough to use the data in climate studies (Saltikoff et al., 2019). In the last decade various studies have used multi-year single polarization weather radar data successfully ~~to a good effect~~ in deriving rainfall climatology with high spatiotemporal resolution (Overeem et al., 2009; Goudenhoofdt et al., 2016). However, quantitative precipitation estimation (QPE) with single polarization C-band radar is strongly affected by attenuation of the electromagnetic wave in heavy precipitation or a wet radome, hail contamination, partial beam blockage and absolute radar calibration (Krajewski et al., 2010; Cifelli et al., 2011).

All prior shortcomings can be mitigated by the use of dual polarization weather radar data. A number of studies have shown that rainfall retrieved from dual polarimetric radar differential phase measurements outperforms rainfall estimated from horizontal reflectivity, especially in heavy precipitation (Wang and Chandrasekar, 2009; Vulpiani et al., 2012; Wang et al., 2013; Crisologo et al., 2014). Because differential phase measurements tend to be noisy and less reliable in low intensity precipitation Crisologo et al. (2014) and Vulpiani and Baldini (2013) improved the robustness of their rainfall retrieval technique by employing a combination of horizontal radar reflectivity $R(Z_H)$ and specific differential phase $R(K_{DP})$ where a threshold was set below which $R(Z_H)$ was used and over which $R(K_{DP})$ was used. Bringi et al. (2011) also compared performances of $R(Z_H)$, $R(K_{DP})$ and the combination product of the two on a relatively long set of data of four years.

The main aim of this study is to evaluate the potential of using polarimetric weather radar QPE for climatological evaluation of precipitation regimes. Previous studies where the benefits of dual polarimetric radar QPE have been shown are mostly based on selected short time periods or only single events (Wang and Chandrasekar, 2010; Chang et al., 2016; Cao et al., 2018). The uniqueness of this paper is ensured by various features. First of all, we have a long multi-year dataset, starting already from 2011, derived by operational dual polarimetric C-band weather radar made by different manufacturers. The dataset is gathered from the archive of weather radar scans set up for operational surveillance in the meteorological services. Secondly, the study areas are from heterogeneous climatologies being the weather radar located in Estonia and Italy. What is more, we will assess the effect of radar scan interval as the radar data scan frequency is 5 and 15 minutes from Italy and Estonia respectively. The study analyses results first at a few selected cases. The whole dataset is analysed at three accumulation intervals of 1 hour, 24 hours and one month. This is also the first ever study evaluating weather radar QPE in Estonia. Automatic rain gauge data are used as reference of radar based products. Based on this dataset we investigate the performance of different rainfall retrieval methods. Horizontal reflectivity data are re-calibrated using a combined set of polarimetric self-consistency techniques (Gorgucci et al., 1992; Gorgucci et al., 1999; Gourley et al., 2009). Rainfall estimations based on K_{DP} are derived from the unwrapped differential phase profile. As a third radar QPE product, an $R(Z_H)$ and $R(K_{DP})$ combination is also generated. All these weather radar-based QPE products are then compared with gauge accumulations.

The paper is organized as follows. Section 2 describes the rainfall estimation datasets from radar and rain gauges and methods used for comparisons. The results are discussed in Sect. 3. In Sect. 4 conclusions are provided.

2. Data and methods

2.1 Rain gauge measurements

In Estonia major renewal and automation of the rain gauge network run by the Estonian Environment Agency (EstEA) started in 2003. Since 2003 to 2006 the network was updated to automatic tipping-bucket gauges. Starting from 2006 the tipping-bucket gauges were progressively replaced by weighted gauges. This process was finished by the end of the year 2011. By that time there were 33 automatic weighted gauge stations and 27 stations with tipping-bucket gauges. According to the comparison study of parallel measurements of the tipping-bucket gauges and weighted gauges the latter exhibited much higher quality (Alber et al., 2015). From the end of 2010 the data has been recorded with 10 minute interval. Until 2010 the temporal resolution was one hour. Both 10-minutes and 1-hour data are being saved by EstEA since then, but only one hour data have been quality controlled by EstEA staff. Because the 10-minutes data are not quality controlled one hour gauge data was used in this study as a more reliable ground truth. The off-line manned data quality control includes using mainly weather sensor data as an additional source for comparisons but also neighbouring stations and weather radar data on some occasions. Only weighted gauge data was used because of the higher quality of these measurements and to ensure uniformness of the dataset. In this work 8 rain gauges close to Sürgavere, Estonia are included (Fig. 1). Data is with 0.1 mm resolution.

Since 1987, Arpa Piemonte, the regional agency for environment protection in Piemonte, Italy, operates the regional automatic gauges network made by about 380 tipping-bucket gauges. Most of the gauges are heated to avoid solid precipitation accumulation during the cold season. The temporal resolution of the gauges network is 1-minute~~ with 0.2 mm resolution data~~. The Arpa Piemonte weather stations are equipped with CAE PMB2 tipping-bucket rain gauges. Their resolution (0.2 mm) is the amount of precipitation for one tip of the bucket. The working range of measures is from zero mm to 300 mm/h with underestimation for high precipitation intensities. Such errors are corrected according to results of WMO Field Intercomparison of Rainfall Intensity Gauges (Vuerich et al., 2009). Automatic data quality check is run on real time data, followed by off-line manned data validation. In this study a network subset made of 42 rain gauges close to Torino, Italy, have been considered (Fig. 1). Precipitation measurements range from 2012 to 2016.

2.2 Weather radar precipitation estimation

Data from C-band dual polarization Doppler weather radars in Estonia and Italy were used in this study. The weather radars considered in this study are from different manufacturers, in Estonia Vaisala WRM200 and in Italy Leonardo Germany Gmbh METEOR 700C radar. Figure 1 illustrates the location of Estonian radar (Sürgavere) and Italian radar (Bric della Croce) together with the locations of available rain gauges.

Sürgavere radar, located in central Estonia at altitude 128 m a.s.l., has been operational since May 2008 but for this study data starting from 2011 was used because the gauge network was updated by that time. The radar performs a surveillance volume scan at 8 elevation angles (0.5°, 1.5°, 3.0°, 5.0°, 7.0°, 9.0°, 11.0° and 15.0°) every 15 min starting each scan from the lowest elevation angle. Only the lowest elevation angle data were used. The resolution of the raw radar data is 300 m in range and 1° in azimuth. Data up to 10 km from radar were discarded because of the ground clutter and unreliable K_{DP} estimation. Close to the radar stable and reliable differential phase observations are not available due to both the antenna itself and the TR-limiters response time or the dual-pol switch in case of alternate transmission. Doppler filter was used to eliminate residual non-meteorological fixed clutter. In addition to speckle and clutter to signal ratio filtering at the signal processor level polarimetric hydrometeor classification was used to filter non-meteorological targets from the display (Chandrasekar et al., 2013). After careful analysis some of the data from Sürgavere radar had to be omitted completely. Years 2014 and 2015 were excluded because of gradually decreasing polarimetric data quality caused by a broken limiter which was replaced in March 2016. Data from 2017 was discarded because the quality was inconsistent as a result of a broken stable local oscillator (STALO) which was replaced in May 2018. From Estonia the investigated period ranges then from 2011-2018 and includes 5 years of data.

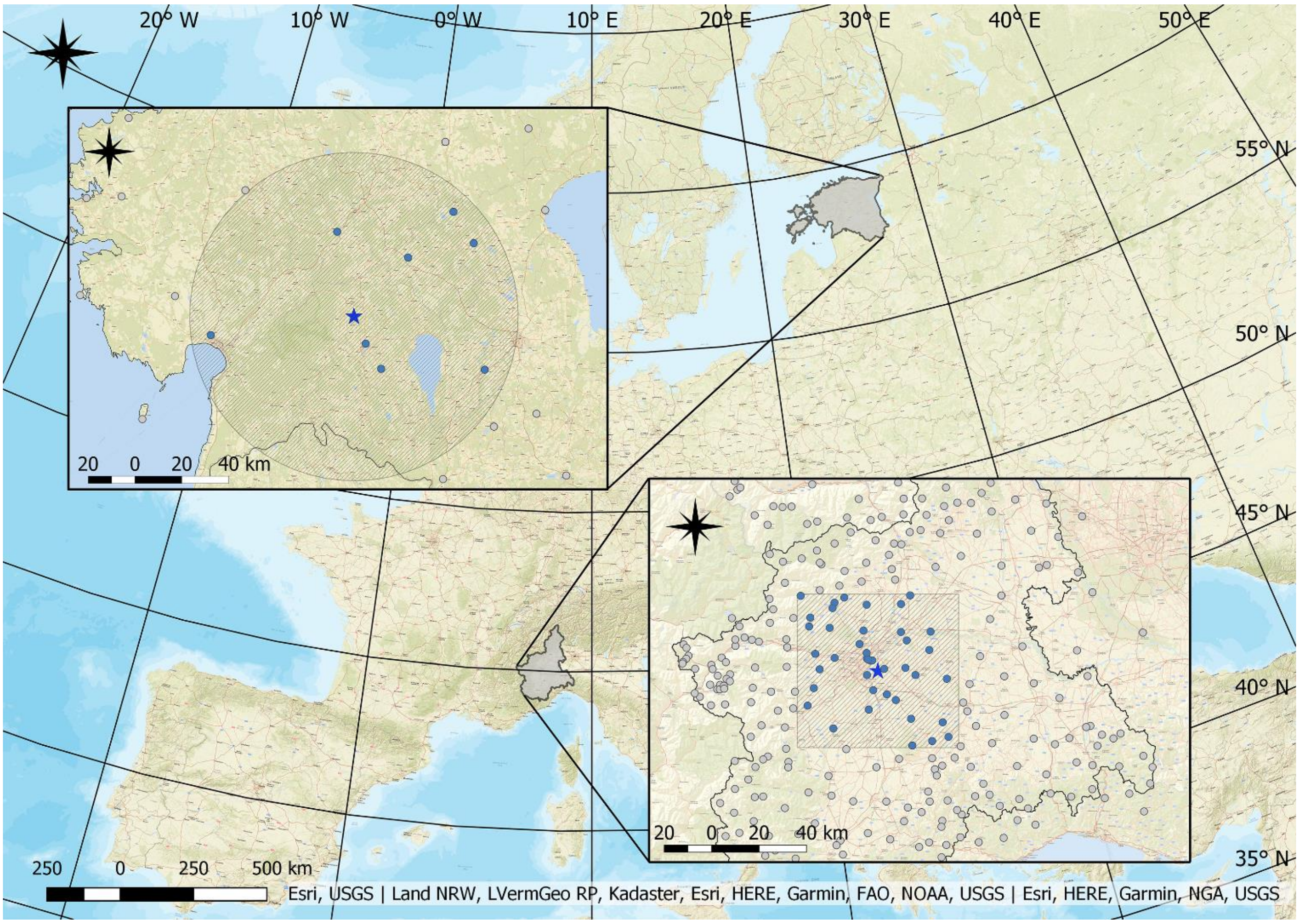


Figure 1. Study areas (shaded) located in Estonia (upper left zoomed area) and in Piemonte, Italy (lower right zoomed area). Grey dots denote gauge locations of Estonian and Piemonte region respectively and blue dots gauges inside the study area. Blue stars reveal radar locations.

On the Torino hill, at altitude 770 m a.s.l., the operational dual-polarization Doppler C-band weather radar Bric della Croce is located. The radar site is in the central part of~~respect~~ Piemonte ~~extent~~region: toward west and north at about 20 km Alps start with peaks 2,500 - 3,000 meters above sea level. The radar performs a fully polarimetric volume scans, made by eleven elevations up to 170 km range, with 340 meters range bin resolution. Bric della Croce observations used in the study range from 2012 to 2016 whereas observations from 2012 to 2013 are with ten-minutes~~-~~ interval and from 2013 to 2016 with five minutes interval time resolution~~ later~~. As can be seen from Fig. 1 circular area around the radar is used in Estonia but in Italy rectangular area is used. The reason for this is that orography in Piemonte is very complex ranging from flat plains in the Po valley (about 100 m a.s.l.) to the Alps up to more than 4,000 m a.s.l. The Bric della Croce weather radar is located on Torino hill that is about 30 km from the Alps. Therefore, the elegant and simple limitation in range by some kilometres from the radar site does not work. To avoid mountainous areas, where partial and total beam-blocking, heavy ground contamination increases, a rectangle area, that extends towards flat grounds, has been preferred.

QPEs, based on horizontal reflectivity, are extensively described by Cremonini and Bechini (2010) and by Cremonini and Tiranti (2018), meanwhile K_{DP} precipitation estimates are derived according to Wang et al. (2009). When K_{DP} was equal to or less than zero, then $R(K_{DP})$ was set to zero. The area close to the weather radar up to eight ~~kilometers~~kilometres has been left out due to heavy ground clutter contamination and unreliable estimations of K_{DP}.

Sürgavere radar specific differential phase (K_{DP}) and differential propagation phase (ϕ_{DP}) were recalculated from raw ϕ_{DP} data using Py-ART function phase_proc_lp (Giangrande et al., 2013) with carefully tuned parameter values according to data specifics. With default parameter values the rays where differential propagation phase folding occurred did not unfold correctly and thus the function did not produce correct specific differential phase values. In order to fix the folding issue function parameters *self_const* (self-consistency factor) and *low_z* (low limit for reflectivity – reflectivity below this value is set to this limit) had to be tuned. The default values were 60000.0 and 10.0 respectively and after testing with various combinations of various values the values 12000.0 and 0.0 were found to produce optimal results and therefore were chosen for final calculations. Horizontal reflectivity (Z_H) was re-calibrated using a method that utilizes the knowledge that Z_H, Z_{DR} (differential reflectivity) and K_{DP} are self-consistent with one another and one can be computed from two of the others. Z_{DR} is not suitable for QPE on C-band radars, but it can be used in this calibration methodology after applying strict restrictions on the data used for this purpose. The calibration was carried out using the self-consistency theory set down in Gorgucci et al. (1992) and Gourley et al. (2009) where the methodology is described in detail. The method essentially compares the observed differential propagation phase (ϕ_{DP}^{obs}) to a calculated theoretical differential propagation phase (ϕ_{DP}^{th}). The data used for calibration had to be filtered using a number of restrictions: only data from June to September was allowed; data from 0.5° elevation and 10-70 km range only used; only bins where horizontal and vertical polarization channel correlation coefficient was over 0.92 were used; any bins where ϕ_{DP} was greater than 12° were removed; whole ray where reflectivity was greater than 50 dBZ was removed; whole ray where Z_{DR} was greater than 3.5 dB was rejected; only rays where $\Delta\phi_{DP}^{obs}$ was greater than 8° and where the consecutive rain path was at least 10 km were used; any scans in which precipitation occurred on top of the radome were removed. As a result Z_H bias values from the range of -2.0 to -5.0 dB were obtained depending on date. The bias values were used to correct the corresponding observed Z_H prior to rain rate estimation.

In order to convert reflectivity Z_H to rainfall rate R (mm/h) the following relation was used:

$$Z_H = 300R^{1.5}. \tag{1}$$

Specific differential phase K_{DP} was converted to rainfall rate using the expression suggested by Leinonen et al. (2012):

$$R = 21.0K_{DP}^{0.720}. \tag{2}$$

The QPE of $R(Z_H)$ can be affected by attenuation on C-band radars especially in heavy precipitation and at long distances. While this can be corrected using ϕ_{DP} in our study it was not applied to the reflectivity data in order to not introduce another possible source of error between the results of Estonia and Italy that could not be easily quantified. Effectiveness of attenuation correction using ϕ_{DP} is hampered by its temperature, shape and size distribution dependence which affect the accompanying error (Vulpiani et al., 2008). The QPE of $R(Z_H)$ can also be affected by the effect of non-uniform vertical profile of reflectivity (VPR). In the current study the effect of VPR will be limited because only data from warm season was used and distance limits to the radar data were set (70 km for Estonia and 30 km for Italy, respectively).

A number of studies have shown that $R(K_{DP})$ provides much more reliable intensity estimates in heavy rainfall (Vulpiani et al., 2012; Wang et al., 2013; Chen and Chandrasekar, 2015). On the other hand it has been indicated that K_{DP} retrieval itself is less reliable in light precipitation conditions (Giangrande and Ryzhkov, 2008; Ryzhkov et al., 2014). Thus combining the two methods has the potential to be superior to using each method separately. For example Vulpiani et al. (2013) used a weighted combination of $R(Z_H)$ and $R(K_{DP})$ where only reflectivity data was used for bins with K_{DP} less than or equal to 0.5 °/km and K_{DP} was used additionally with increasing weight over that value up to 1 °/km over which it was solely used. Cifelli et al. (2011) used simple threshold method where $R(K_{DP})$ was used when $R(Z_H)$ was exceeding 50 mm/h intensity. Several authors have successfully added $R(Z_{DR})$ based intensity estimation to the combination on S-band weather radars (e.g. Ryzhkov and Zrnic, 1995; Ryzhkov et al., 2005; Chandrasekar and Cifelli, 2012). Due to residual effects such as resonance, noise and attenuation $R(Z_{DR})$ should not be used at C-band (Ryzhkov and Zrnic, 2019).

In our study rainfall from a combined threshold approach was used for both weather radars as a third product $R(Z_H,K_{DP})$. In the combined product $R(Z_H)$ was used in areas with Z_H less than or equal to 25 dBZ and $R(K_{DP})$ otherwise if available. The Z_H

threshold value was selected after testing with various reflectivity levels. The threshold level is considerably lower than some of the thresholds used in the literature but on our datasets it performed the best.

2.3 Comparison framework

In order to estimate the performance of the radar rainfall products they were compared with gauge accumulations. The study period was limited to the warm season (May - September for Estonia and April - October for Italy). In Estonia, the mean annual precipitation is 649 mm. Precipitation climatology has distinct seasonality with maxima in summer (215 mm) followed by autumn (198 mm), winter (128 mm) and spring (108 mm). The summer maxima of seasonal mean precipitation is especially pronounced in the continental part of Estonia (246 mm in Mauri, South-East Estonia), Tammets et al. (2013).

In Piemonte, close to the radar, the mean annual precipitation is 870 mm having bimodal distribution with peaks in spring (266 mm) and in autumn (255 mm), Devoli et al. (2018).

Maximum distance of the gauges to be included in the comparison was limited to 70 km radius from radar location in case of Estonia and up to 30 km distance in Italy. Thus, in Estonia and in Italy rainfall data were from 8 and 42 gauges respectively. By limiting data analysis to warm season and constraining the maximum radar range, we were able to ensure that radar data were originating mainly~~only~~ from liquid precipitation (hail can also occur) which is required for more reliable rainfall intensity estimation. Possible occurrence of hail was not removed from the data because of the intention to keep additional data processing minimal and allow level comparison of the various QPE methods.

In the case of Italy, the applied range limit is also aimed at eliminating uncertainties due to complex orography, like shielding by the mountains, overshooting, bright band contamination. Up to 30 km from Bric della Croce, terrain is relatively flat, while beyond that mountains block most of the radar signal for lowest elevations.

Radar-based QPEs have been accumulated to 1-hour duration and longer durations have been calculated based on~~y~~ these accumulations. Accumulations were calculated by adding subsequent instantaneous radar QPE values without any space-time interpolation. No missing data for radar or gauges was tolerated to prevent underestimation. A threshold of 0.1 mm was set and applied such that both gauge and radar QPE values must exceed this value to make the pair valid.

The quality of the rainfall estimates was estimated by the following verification measures (where r_i is the i-th out of n radar precipitation estimates, g_i the i-th out of n gauge observations, r_m the mean of all n radar precipitation estimates, and g_m the mean of all n gauge observations):

Pearson's correlation coefficient: $CC = \frac{\sum_{i=1}^{n}(r_i-r_m)\cdot(g_i-g_m)\cancel{\sum_{i=1}^{n}(g_i-g_m)}}{\sqrt{\sum_{i=1}^{n}(r_i-r_m)^2}\cdot\sqrt{\sum_{i=1}^{n}(g_i-g_m)^2}}$, (3)

Normalized Mean Absolute Error: $NMAE = \frac{\sum_{i=1}^{n}|r_i-g_i|}{\sum_{i=1}^{n} g_i}\cancel{\cdot 100\%}$, (4)

Normalized Mean Bias: $NMB = \frac{\sum_{i=1}^{n}(r_i-g_i)}{\sum_{i=1}^{n} g_i}$, (5)

Root Mean Squared Error: $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(r_i - g_i)^2}$, (6)

Nash-Sutcliffe Efficiency: $NASH = 1 - \frac{\sum_{i=1}^{n}(r_i-g_i)^2}{\sum_{i=1}^{n}(g_i-g_m)^2}$. (7)

The Nash coefficient is typically used to assess accuracy of hydrological predictions, but it has also been used for weather radar-based rain rates and gauges comparisons (Nash and Sutcliffe, 1970).

3. Results and discussion

3.1 Case comparisons

In this section radar ~~rainfall estimation~~QPE products are compared with single location gauge measurements of selected short periods from Estonia and Italy. ~~and on a specific gauge location basis~~. ~~This allows to evaluate how well radar products capture single events and how they follow gauge values on location basis.~~ This allows to evaluate the performance of the radar QPE against gauge measurements from timeseries viewpoint.

Figure 2 shows one month of precipitation on Jõgeva station location (60 km away from the radar site) in Estonia with one hour temporal resolution. Overall radar products follow the gauge measurements well but there are considerable differences among them. Reflectivity based product $R(Z_H)$ is not affected by noise and clutter in clear weather or in light rain cases but on the other hand it is underestimating rainfall amounts particularly in medium to heavy precipitation cases. By the end of the month its sum of 40.5 mm was 19.6 mm less than gauge measured accumulation (70.1 mm). $R(K_{DP})$ then again is heavily overestimating precipitation amounts especially during light rain cases. By the end of the month the accumulated amount of 150.2 mm was more than double of the gauge sum. Third product, $R(Z_H,K_{DP})$, was showing the best performance of all the three compared and it was correlating well with gauge accumulation time series and one month accumulation of 69.5 mm was just 0.6 mm lower than rain gauge sum.

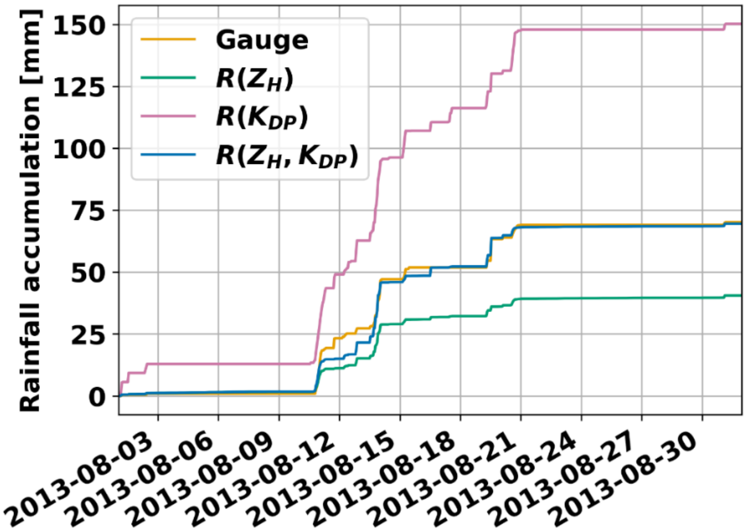


Figure 2. One month 1-hour rainfall cumulative accumulations, Sürgavere radar data, Jõgeva station gauge data.

Gauge and radar accumulations are not always so well correlated as Fig. 3 demonstrates. In this accumulation period there are rainfall events which show that gauge values can be both under- and overestimated by radar products. Rainfall around 11th of June 2016 is overestimated by all radar QPE products with the smallest overestimation by $R(Z_H)$ and greatest by $R(K_{DP})$ which overestimated the gauge by more than double in this event. In the following days until 21st of June 2016 light to medium precipitation was recorded by the gauge and during this time $R(K_{DP})$ mostly overestimated the gauge accumulations while $R(Z_H)$ underestimated rainfall. On 21st of June 2016 a convective rainfall event occurred during which 51 mm of rainfall was measured in 2 hours with gauge. All radar QPE products underestimated the rainfall amount during this event. By the end of the month-long accumulation period $R(Z_H,K_{DP})$ was closest to the gauge value (underestimation by 16.6 mm) while $R(Z_H)$ underestimated even more and $R(K_{DP})$ again overestimated gauge measurements.

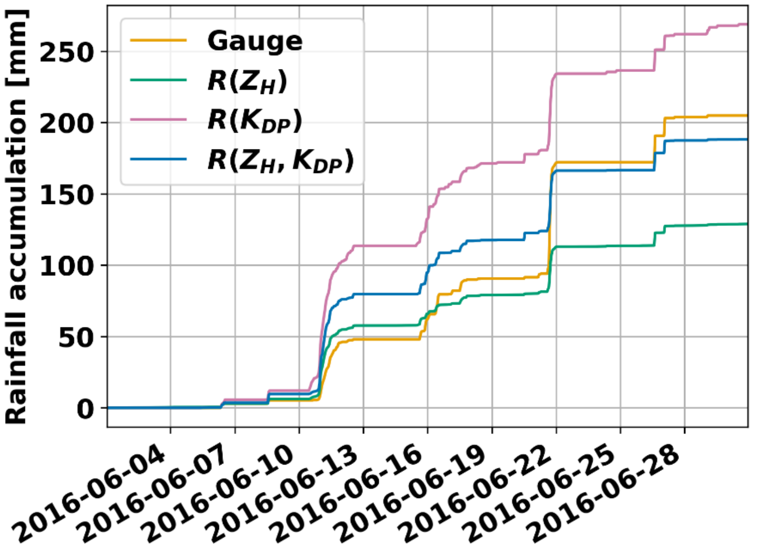


Figure 3. One month 1-hour rainfall cumulative accumulations, Sürgavere radar data, Tartu-Tõravere station gauge data.

Figure 4~~3~~ illustrates a case from Italy, comparison of a gauge located within 30 km distance from radar to Bric della Croce radar precipitation estimation products. In the end of the 34-hour period the specific differential phase based product $R(K_{DP})$ has the smallest error compared to gauge as it overestimates the gauge measurement of 40.6 mm by 2.0 mm. On the other hand in light rain $R(K_{DP})$ is overestimating significantly - in the first 13 hours when gauge measured 3.4 mm of accumulated rainfall it already estimated 12.2 mm. $R(Z_H)$ was underestimating even in light rain and in heavy rain the difference compared to gauge measurement increased further. In the end of the period the underestimation was nearly threefold (15.6 mm compared to gauge accumulation of 40.6 mm). $R(Z_H,K_{DP})$ product showed good correlation with gauge in light precipitation as it was mostly based on reflectivity data, but in more intense precipitation it was still underestimating compared to gauge data. In the end of the period the accumulated value for $R(Z_H,K_{DP})$ was 26.7 mm.

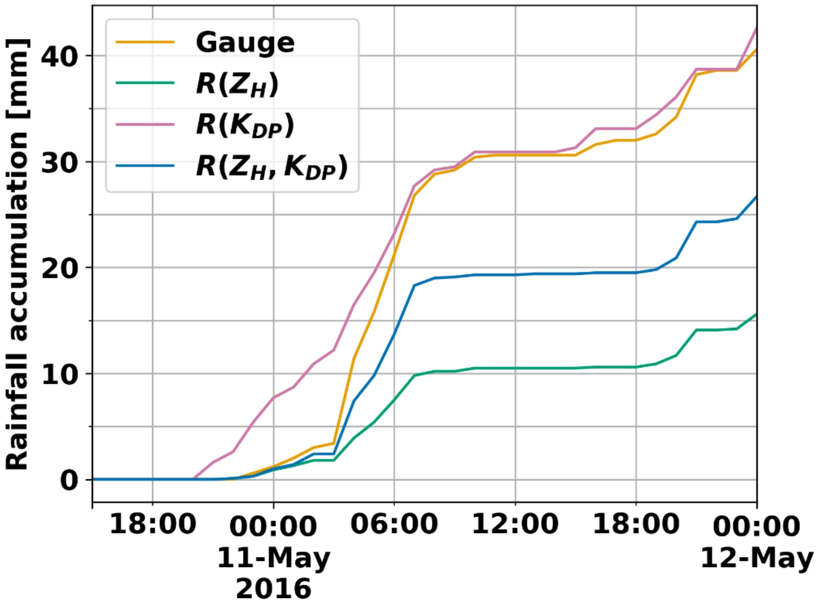


Figure 4~~3~~. 1-hour rainfall cumulative accumulations from Verolengo gauge, located at 29 km from the radar, and co-located Bric della Croce radar QPE.

In all selected~~both~~ cases the general behaviour of QPEs is similar. Weather radar estimations, even when sampled by 15-minutes interval observations, follows gauge measurements with good agreement. ~~It has to be mentioned though that this was~~

~~just one case and there were numerous shorter time period based cases where the 15-minute Estonian radar products did not capture precipitation as well as gauge and missed some events.~~Although the second case from Estonia illustrated well that ~~L~~longer scan interval increases the ~~randomness~~ scatter and particularly with small scale convective precipitation for which minimal sampling interval is the most beneficial. From Italy the example case was much shorter, but the precipitation intensity was higher. On both cases $R(K_{DP})$ generally overestimates precipitation amounts, especially in light rain cases. In Italy the $R(K_{DP})$ overestimation is smaller. One of the causes of this behaviour might be more intense precipitation in Italy where K_{DP} measurement became more accurate. More intense rainfall on the other hand caused greater underestimation of $R(Z_H)$ based precipitation accumulation from gauge values compared to Estonia. Another cause of differences between the two countries might be differences in the drop size distribution climatologies. Rainfall retrieval relations also entail errors and to keep the comparison as uniform as possible we decided to use the same relations for both Italy and Estonia. These example cases demonstrated that radar can be used for 1-hour accumulations, but systematic errors cannot be excluded. In order to find out errors and uncertainties and to see how QPEs compare to gauge measurements on longer scale will be looked at in the next sections.

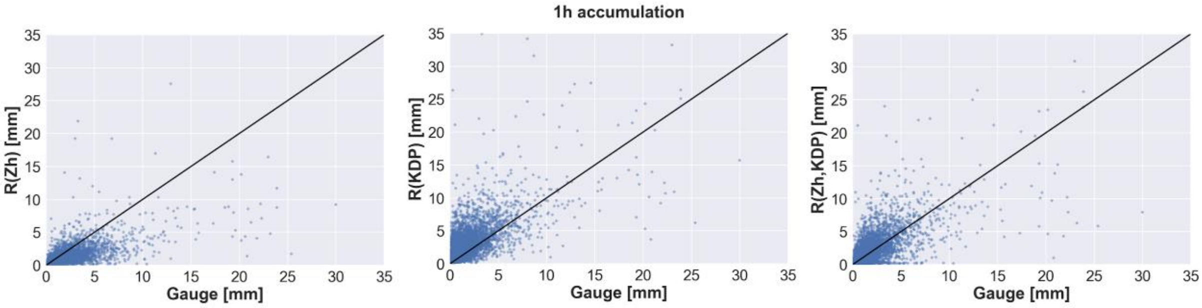
3.2 Comparison of one hour accumulations

The quality of the rainfall estimates is compared at various accumulation intervals. Comparing different intervals can also be useful to point out representativeness issues caused by low radar scan rates. Investigated period covers the years 2011-2018 in Estonia and 2012-2016 in Italy.

First, in this section hourly accumulations are analysed. Hourly accumulations are especially important for small basins and in extreme precipitation climatology analysis. Hourly rainfall maxima can provide valuable data for flash flood nowcasting and other hydrological applications.

Table 1. Verification of the radar-based rainfall 1-hour accumulation products of Estonia.

	$R(Z_H)$	$R(K_{DP})$	$R(Z_H,K_{DP})$
CC	0.679	0.674	0.697
NMAE	0.537	0.868	0.594
NMB	-0.143	1.861	0.298
RMSE(mm)	1.615	2.131	1.677
NASH	0.214	-0.037	0.184



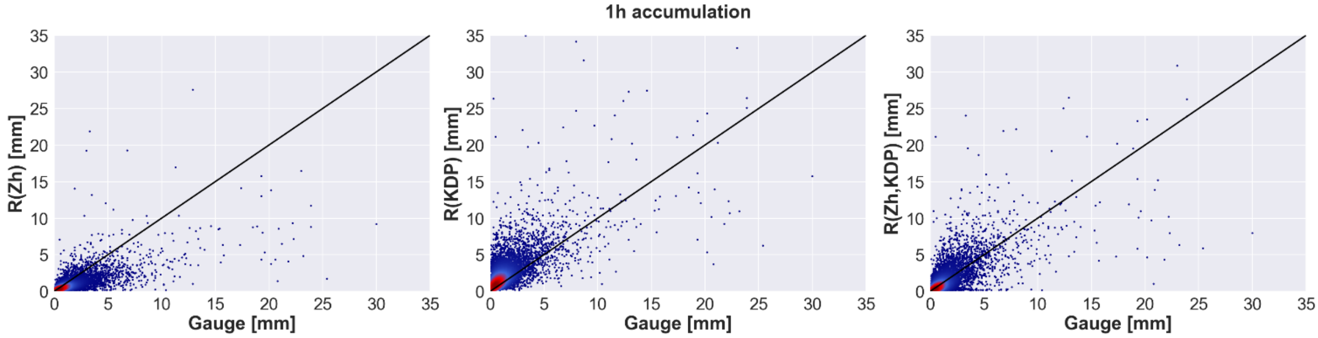


Figure 5~~4~~. Scatter plots of radar-based rainfall estimates against rain gauge observations for 1-hour accumulation intervals in Estonia 2011-2018. The corresponding verification measures are presented in Table 1. Number of radar-gauge data pairs with 8 gauges and accumulations > 0.1 mm is 7,019.

Table 1 presents the verification results for the hourly accumulation interval in Estonia. Figure 5~~4~~ shows the corresponding scatter plots. As can be seen, the $R(Z_\mathrm{H})$ estimation generally underestimates rainfall, especially heavy events while it has the best error verification values (Nash-Sutcliffe Efficiency 0.214, NMAE 0.537, NMB -0.143 and RMSE 1.615 mm). $R(K_\mathrm{DP})$ on the other hand overestimates accumulations for low intensity events as could be presumed. $R(Z_\mathrm{H},K_\mathrm{DP})$ shows considerable improvement by combining strong aspects of the two methods~~in both other product's weak points as it captures heavy rainfall events better and does not underestimate weak precipitation~~. It has the highest correlation coefficient (0.697) of all the products. Nevertheless, it can be seen from the scatterplots that there is a lot of scatter~~randomness~~ in the hourly radar accumulations with all products. Mostly, it can be linked to the low spatial representativeness of the point measurements of rain gauges. This effect is more pronounced on a short time scale and it~~they~~ originates from scarce gauge network and insufficient~~low 15-minute~~ radar scan rate. Small scale effects like wind drift might also be more influential on shorter accumulation period (Lauri et al., 2012). The reason why $R(Z_\mathrm{H})$ might have the best performances when NMAE and RMSE are considered is because there are not very many heavy rainfall cases in Estonia and this tends to favour $R(Z_\mathrm{H})$ in the verification comparisons.

From Italian hourly accumulation scatterplots in Fig. 6~~5~~, it can be seen that the overall behaviour of the radar products is similar to Estonia. Although from Fig. 6 it can be noticed that of the four highest 1-hour accumulations measured by the gauge, three of them have significantly higher radar estimates for $R(Z_\mathrm{H},K_\mathrm{DP})$ than either $R(Z_\mathrm{H})$ or $R(K_\mathrm{DP})$. This could be explained by precipitation that was very variable in intensity and also in spatial coverage in these three cases which in turn caused unsteady behaviour of the precipitation estimates. Z_H underestimates high intensities, but with low intensities K_DP becomes noisy and the rainfall intensity estimation is not feasible. Finally, to reduce K_DP uncertainties range averaging is mandatory, leading to underestimation in case of very localized showers. By blending both $R(Z_\mathrm{H})$ and $R(K_\mathrm{DP})$, a better rainfall estimation is expected. Table 2 presents the corresponding verification results. $R(Z_\mathrm{H})$ underestimates particularly at intense precipitation events. $R(K_\mathrm{DP})$ generally overestimates hourly accumulations especially at low intensity cases: as stated by Wang et al. (2013), $R(K_\mathrm{DP})$ generates noisier estimations at low rain rates. $R(Z_\mathrm{H},K_\mathrm{DP})$ outperforms both other products in Italy which is confirmed by verification metrics as it overcomes the shortcomings of the other estimations.

Less random scatter is visible in Italian hourly data due to more frequent scan strategy. $R(Z_\mathrm{H})$ is underestimating more than in Estonia as expected because in Italy intense rainfall is more frequent - it has larger RMSE and even more negative NMB. Probably for the same reason $R(K_\mathrm{DP})$ is more accurate in Italy than in Estonia as it has smaller NMAE and NMB while having larger RMSE due to higher rainfall intensities recorded in Italy.

Table 2. Verification of the radar-based rainfall 1-hour accumulation products of Italy.

	$R(Z_\mathrm{H})$	$R(K_\mathrm{DP})$	$R(Z_\mathrm{H},K_\mathrm{DP})$
CC	0.843	0.808	0.870

NMAE	0.531	0.514	0.423
NMB	-0.296	0.678	0.120
RMSE(mm)	3.136	3.037	2.750
NASH	0.364	0.385	0.443

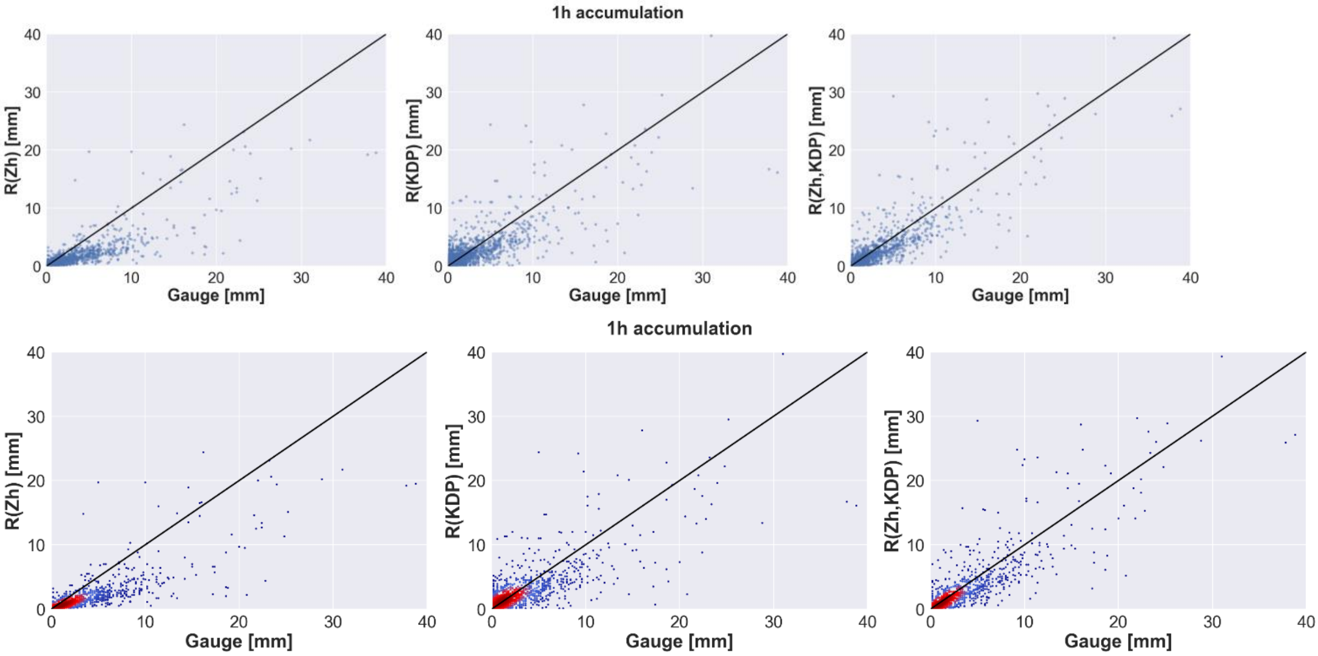


Figure 6~~5~~. Italy 1-hour accumulations 2012-2016. The corresponding verification measures are presented in Table 2. Number of radar-gauge data pairs with 42 gauges and accumulations > 0.1 mm is 1,233.

3.3 Comparison of 24-hours accumulations

Table 3 shows the verification results for the daily accumulation interval in Estonia, while Fig. 7~~6~~ presents the corresponding scatter plots. As expected, much less scatter can be seen than on the daily~~hourly~~ level but overall the results are consistent with the hourly interval verification outcomes. Using longer accumulation intervals leads to less severe errors as the longer period compensates for both underestimates and overestimates. Reflectivity based product, *R*(Z_H), is still underestimating rain depths while the negative bias is considerably smaller than in hourly interval data. By looking at the definition of NMB in Eq. (5) it can be seen that in case the same underlying samples are used NMB should be equal on all accumulation lengths. In our study the underlying samples were different as the 0.1 mm threshold was applied after the accumulation as a last step before calculating the verification metrics. This emphasizes the importance of low-intensity precipitation for total accumulations. *R*(K_{DP}) is the least accurate of the three products also on daily accumulation level with the lowest correlation and highest error scores. The combined product, *R*(Z_H,K_{DP}), removes the negative bias of *R*(Z_H) and shows better correlation and substantial improvement in terms of both the systematic error and the overall error compared to *R*(K_{DP}). *R*(Z_H,K_{DP}) has the smallest NMAE of 0.438, RMSE of 3.992 mm and highest Nash-Sutcliffe Efficiency equal to 0.392. Overall there is noticeably less ~~randomness~~ scatter in the daily radar accumulations compared to 1-hour interval.

Table 3. Verification of the radar-based rainfall 24-hours accumulation products of Estonia.

	R(Z_H)	*R*(K_{DP})	*R*(Z_H,K_{DP})
CC	0.831	0.792	0.827

NMAE	0.475	0.845	0.438
NMB	-0.050	2.290	0.343
RMSE(mm)	4.366	7.195	3.992
NASH	0.335	-0.097	0.392

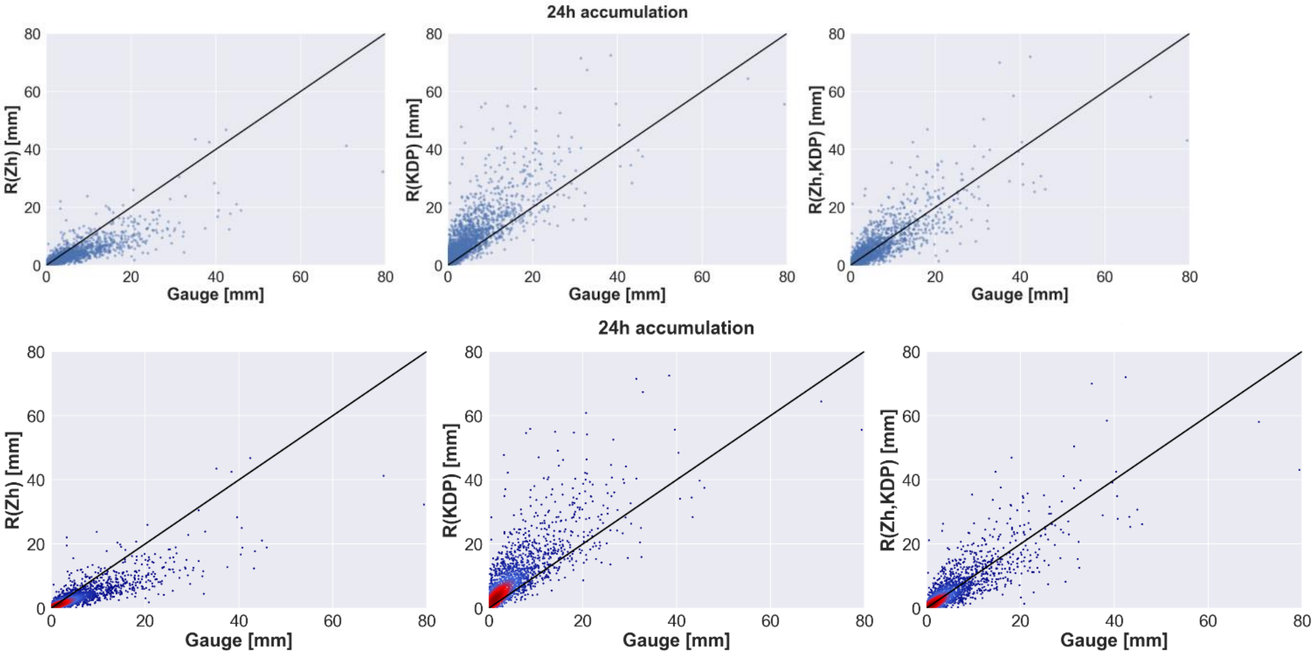


Figure 7~~6~~. Estonia 24-hours accumulations 2011-2018. The corresponding verification measures are presented in Table 3. Number of radar-gauge data pairs with 8 gauges and accumulations > 0.1 mm is 2,148.

Table 4 shows the verification results for the daily accumulation interval in Italy, while Fig. 8~~7~~ presents the corresponding scatter plots. $R(Z_H)$ is slightly underestimating compared to gauge results and surprisingly it outperforms other competing products in all metrics except Pearson's correlation coefficient. $R(K_{DP})$ is again overestimating the most and has the lowest correlation with gauge data. $R(Z_H,K_{DP})$ notably improves the $R(K_{DP})$ on all verification metrics but does not exceed $R(Z_H)$ except for correlation coefficient which is the highest of all three products with r of 0.708. In Italy the decrease in ~~randomness~~ scatter of radar accumulations cannot be observed compared to 1-hour level. On Fig 7. two regimes can be observed and we assume that VPR correction leads to these regimes. Bric della Croce weather radar is located on a top of hill at 770 m a.s.l. and during the winter season a vertical profile reflectivity correction (VPR) is applied (Koistinen, 1991). This correction is manually switched on at the beginning of the cold season and it is switched off at the end. In case of convective precipitation, this correction may lead to rainfall overestimation. On the other hand, stratiform cold precipitation is heavily underestimated when VPR correction is switched off.

Table 4. Verification of the radar-based rainfall 24-hours accumulation products of Italy.

	$R(Z_H)$	$R(K_{DP})$	$R(Z_H,K_{DP})$
CC	0.692	0.661	0.708
NMAE	0.504	0.636	0.553
NMB	-0.01	0.789	0.459
RMSE(mm)	8.909	11.071	10.552

NASH	0.238	0.054	0.098

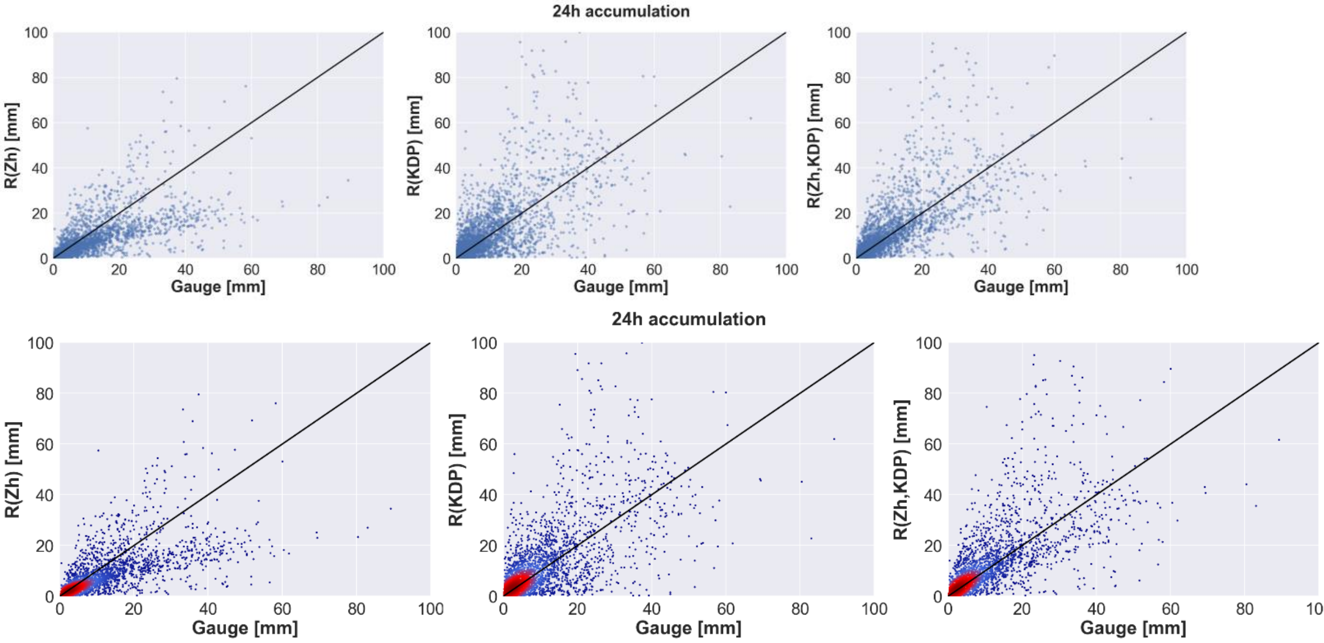


Figure 8~~7~~. Italy 24-hours accumulations 2012-2016. The corresponding verification measures are presented in Table 4. Number of radar-gauge data pairs with 42 gauges and accumulations > 0.1 mm is 3,010.

3.4 Comparison of monthly accumulations

Table 5 shows the verification results for the monthly accumulation interval in Estonia, while Fig. 9~~8~~ presents the corresponding scatter plots. Compared to shorter time scales overall on monthly scale the correlation of all the products with gauge accumulations is higher. $R(Z_H)$ is underestimating with larger mean bias (-0.284) than on daily level but with smaller normalized mean absolute error (0.360). $R(K_{DP})$ is showing less scatter than on shorter time scales like other products while still heavily overestimating accumulations (NMB equal to 1.042 with RMSE equal to 62.466 mm). On monthly accumulation level $R(Z_H, K_{DP})$ outperforms the two other products to a great extent. It is well correlated to gauge values with small scatter as it is performing great both in low and high accumulation cases. The correlation coefficient is nearly identical to $R(Z_H)$, but it removes the systematic underestimation of $R(Z_H)$ and overestimation of $R(K_{DP})$ and exceeds them in all other verification metrics.

Table 5. Verification of the radar-based rainfall monthly accumulation products of Estonia.

	$R(Z_H)$	$R(K_{DP})$	$R(Z_H,K_{DP})$
CC	0.877	0.789	0.875
NMAE	0.360	0.822	0.214
NMB	-0.284	1.042	0.109
RMSE(mm)	27.448	62.466	16.704
NASH	0.155	-0.924	0.486

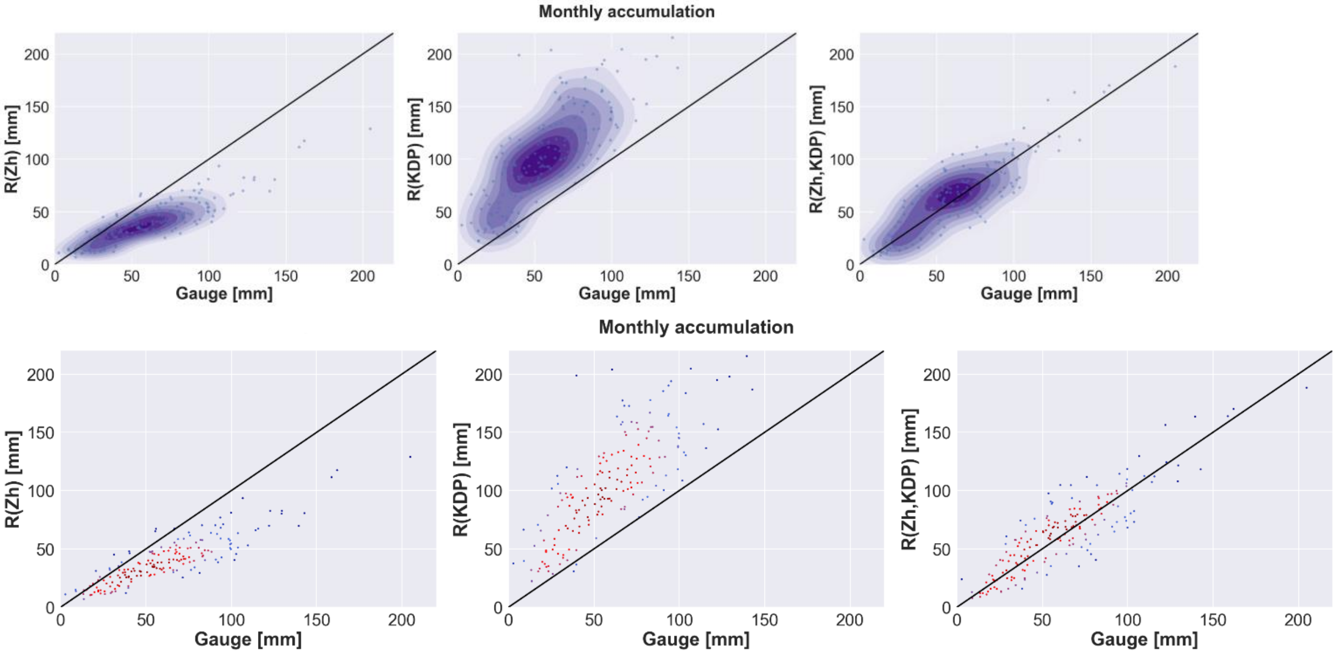
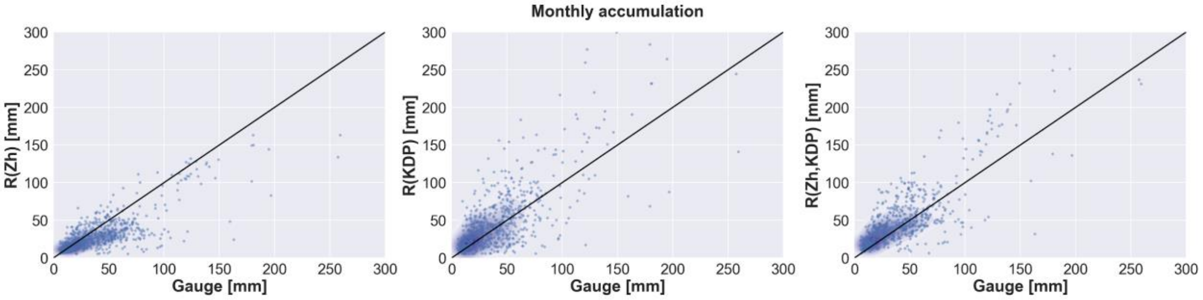


Figure 9~~8~~. Estonia monthly accumulations 2011-2018. The corresponding verification measures are presented in Table 5. Number of radar-gauge data pairs with 8 gauges is 179.

Table 6 shows the verification results for the monthly accumulation interval in Italy, while Fig. 10~~9~~ presents the corresponding scatter plots. Scatterplots reveal similar characteristics to the daily level accumulations of the products. $R(Z_H)$ is underestimating rainfall also on monthly scale and $R(K_{DP})$ overestimating. $R(Z_H, K_{DP})$ is still overestimating but with a decreased RMSE compared to $R(K_{DP})$ product. It also exhibits the highest correlation coefficient of the three. According to the verification results most of the metrics indicate better performance of the radar products on monthly scale compared to daily intervals. Correlation coefficient is higher and NMAE is lower on all the products when the two timescales are compared.

Table 6. Verification of the radar-based rainfall monthly accumulation products of Italy.

	$R(Z_H)$	$R(K_{DP})$	$R(Z_H,K_{DP})$
CC	0.776	0.726	0.799
NMAE	0.375	0.488	0.408
NMB	-0.128	0.310	0.337
RMSE(mm)	23.737	30.802	24.914
NASH	0.288	0.076	0.253



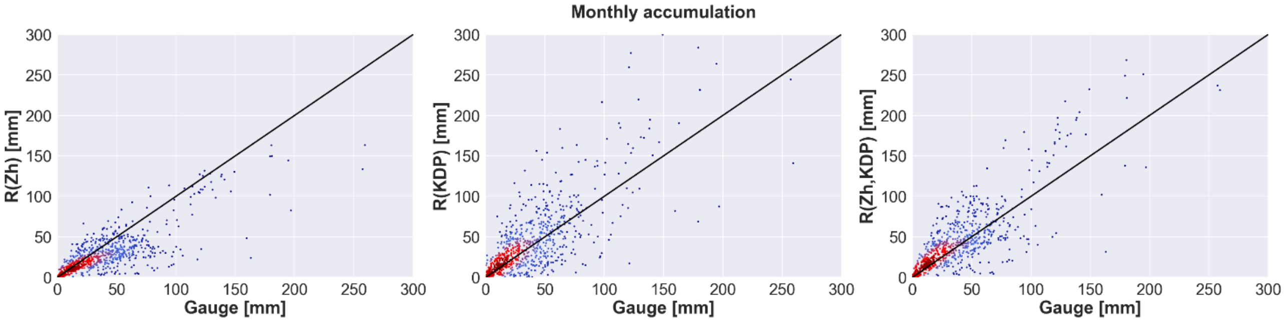


Figure 10~~9~~. Italy monthly accumulations 2012-2016. The corresponding verification measures are presented in Table 6. Number of radar-gauge data pairs with 42 gauges is 675.

4. Conclusions

In the present study polarimetric rainfall retrieval methods for the fully operational C-Band radars in Sürgavere, Estonia and Bric della Croce, Italy have been analysed. The study focuses on the warm period of the year and long period of multi-year data is used. From Estonia five years data from 2011 to 2018 has been included, from Italy the data interval ranges from 2012 to 2016. Reflectivity data were calibrated following a self-consistency theory and measured horizontal reflectivity (Z_H) was corrected accordingly. In order to calculate rainfall from polarimetric variables, differential propagation phase (ϕ_{DP}) was reconstructed and based on that specific differential phase (K_{DP}) retrieved. To achieve this the transparently implemented algorithm phase_proc_lp (Giangrande et al., 2013) in the open source toolkit Py-ART was used for Estonian data. For Italian data, K_{DP} precipitation estimates were obtained following the theory set down in Wang et al. (2009).

Three radar rainfall estimation products were computed: horizontal reflectivity based product $R(Z_H)$, specific differential phase based product $R(K_{DP})$ and a combined product based on the previous two $R(Z_H,K_{DP})$. Rain gauge network data of Italy and Estonia were used as ground truth. 1-hour, 24-hours and monthly accumulations were derived from the radar products and gauge data.

Time series comparison revealed that even with 15-minute scan interval radar is suitable for QPE, at least with more widespread precipitation like stratiform rain. Still on the shortest accumulation period of 1-hour the more scarce radar data from Estonia had more ~~random~~ scatter than data from Italy where the scan interval was 10 minutes on older data and 5 minutes since 2013. As an overall trend, the longer the accumulation period the less ~~random~~ scattering was visible.

When the three products are compared to each other in case of Estonia the $R(Z_H,K_{DP})$ was clearly superior to $R(Z_H)$ and $R(K_{DP})$ on all accumulation periods. Especially on monthly accumulation scale it was performing distinctly better as it had RMSE 39% lower than the nearest competitor, the $R(Z_H)$ product and even 73% lower than $R(K_{DP})$. In Italy the $R(Z_H,K_{DP})$ product was exceeding the two others clearly on hourly level. On 24-hours and monthly accumulation scale it had the highest correlation with gauge measurements but the error verification measures were slightly higher than those of the $R(Z_H)$. Nevertheless it outperformed $R(K_{DP})$ on all timescales.

Overall the results show that the combined product $R(Z_H,K_{DP})$ performs better on almost all of the verification measures in both countries compared to $R(Z_H)$ and $R(K_{DP})$ as it uses successfully the benefits of each other product and eliminates the weaknesses. $R(Z_H)$ was good at low precipitation intensities but in general it was underestimating precipitation. It had an average NMB of -0.159 over all the accumulation lengths in case of Estonia and -0.145 in Italy. $R(K_{DP})$ was performing well at higher intensities but in general was overestimating precipitation. It had an average NMB of 1.731 over all the accumulation lengths in case of Estonia and 0.592 in Italy. While the combined product $R(Z_H,K_{DP})$ was slightly overestimating precipitation with an average NMB of 0.250 over all the accumulation lengths in case of Estonia and 0.305 in Italy. In both countries the $R(Z_H,K_{DP})$ product also had the highest average CC over all the accumulation lengths with CC of 0.800 in Estonia and 0.792

in Italy. Generally the CC was higher the longer the accumulation period was with the highest CC in monthly accumulations ($R(Z_H,K_{DP})$ CC of 0.875 in Estonia and 0.799 in Italy).

~~The products were behaving similarly in Estonia and Italy also in the way that $R(Z_H)$ was underestimating and $R(K_{DP})$ overestimating precipitation.~~ In case of Estonia ~~the underestimation of $R(Z_H)$ was less than in Italy and~~ the overestimation of $R(K_{DP})$ was noticeably higher than in Italy. We hypothesize that this is mostly due to different climatological regimes between Italy and Estonia as higher intensity rainfalls occur more frequently in Italy. Although one has to keep in mind that the radars were from different manufacturers and thus also the used K_{DP} retrieval algorithms were different which might be the cause of some discrepancy. Another source of error might originate from the implemented Z_H-R and K_{DP}-R relations which might not perform equally in different climates. Overall the results of the study showed that dual polarimetric radar QPE and especially the combined product $R(Z_H,K_{DP})$ show good potential to be used in climate studies if certain limitations are considered.

Synoptic patterns could be used as an additional source for classifying ~~filtering~~ the radar accumulations. This would enable to verify the performance of each radar product on stratiform and convective events. Moreover, it could be used to ~~see~~ investigate ~~that~~ if frequent scans play ~~the~~ bigger role in convective events than stratiform as could be hypothesized and to quantify the effect.

For future studies, it would also be useful to calculate probabilities and return periods of extreme rainfall for weather radar-based rainfall climatology .

Code and data availability. The code used to conduct all analyses in this paper is available by contacting the authors. Gauge and radar data used in this study are available by contacting the authors.

Author contributions. TV, RC, PP and DM directly contributed to the conception and design of the work. TV and RC collected and processed the various datasets and wrote the original draft with input from PP and DM. All authors reviewed and edited the final draft.

Competing interests. The authors declare that they have no conflict of interest.

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